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Eye movements in the visual search of word lists

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Abstract

The word identification span refers to the area of the visual field in which words can be identified during a single fixation. The purpose of the study was to estimate the vertical word identification span in a visual word search task, in which words were arranged in a vertical list. In addition, we studied the effect of list layout (orientation, length, and line spacing) on the speed of search and eye movements. The task of the observer was to identify a target word in a word list, where the other words were distracters. Threshold search time, that is, stimulus presentation time for correct identification at a probability level of 0.79, was determined by using a multiple alternative staircase method. Eye movements were recorded simultaneously. The results showed that, in vertical lists, 4–5 words could be identified during a single fixation. Thus, the vertical word identification span was 4–5 character spaces, whereas according to previous studies the horizontal word identification span is about 10 character spaces, which corresponds to 1–2 words. There were fewer fixations and the saccade amplitudes were smaller for vertical than for horizontal lists of the same length. However, search times did not depend on list orientation. This was due to longer fixation times for vertical lists. Further, since average fixation duration for vertical lists was longer than for horizontal lists, processing time seems to depend on the number of items within the span. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Word search is a variant of the classical *visual search* paradigm (Treisman & Gelade, 1980; see also Wolfe, 1994, 1998). In word search, the task of the observer is to find a target word from a set of distracter words. Since the target and the distracters are quite complex stimuli, word search generally requires serial scanning. When the number of words (set size) is large enough, more than one fixation is required to locate the target word. This is due to the rapid decline of resolution of the visual system as a function of eccentricity (see e.g. Wertheim, 1894; translated into English by Dunskey (1980)). The resolution declines mainly because of the decline of retinal ganglion cell density as a function of eccentricity (Curcio & Allen, 1990). Therefore, letter information can only be acquired from a limited area around fixation.

Visual search has been studied extensively, but in many cases using relatively simple stimuli and without

eye movement recordings. However, many studies in which eye movements have been recorded suggest that eye movement data provide deeper understanding of the perceptual processes in visual search and reading (see Rayner (1998) for review). A number of studies of eye movements during reading deal with several concepts related to the processing of words. However, word recognition in the context of visual search has not been studied as extensively (but see Rayner & Raney, 1996; Rayner & Fischer, 1996).

1.1. Perceptual span and visual span

The area that can be processed during a single fixation is ultimately limited by the decline of visual acuity with eccentricity. Reading studies present several concepts referring to the type of information available around the fixation point. The conceptual framework of the area is somewhat complicated, and many concepts resemble each other. Here we will first discuss the perceptual span, followed by the visual span.

The perceptual span or effective visual field (McConkie & Rayner, 1975) refers to the region from which readers

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pick up various types of information that are useful during a fixation in reading. It includes information about letters that can be recognised, some partial letter/word information, and information about spaces between words. The perceptual span has been extensively studied with the moving window technique developed by McConkie and Rayner (1975), who found that in reading information about word length could be acquired from up to about 12–15 character positions to the right of the fixation point. However, specific information about letters was acquired from no further than 10 characters to the right of the fixation point. Several studies indicate, that for readers of alphabetical orthographies, the size of the perceptual span is about 14–15 letters to the right, and about 3–4 letters to the left of the fixation point (see Rayner (1998) for review).

Osaka and Oda (1991) and Osaka (1992) used the moving window paradigm to estimate the perceptual span for vertically written Japanese to be about 5–6 character spaces in the vertical direction (for mixed kanji and hirakana characters). Their vertical estimate was slightly smaller than the perceptual span estimate for horizontally written Japanese, which was about five character spaces to the right of the fixation for hirakana and seven character spaces for kanji-based mixed text (Osaka, 1992). The horizontal perceptual span for Japanese is clearly smaller than the perceptual span for alphabetical languages (see above). Therefore, the perceptual span seems to be smaller for more densely packed languages, when expressed in character spaces.

On the other hand, in visual search Rayner and Fisher (1987) divided the perceptual span into two complementary parts, *decision* and *preview regions* from which qualitatively different information is acquired. In their experiments, the subjects searched for the specific target letter from horizontal rows of letters, and the visible area was manipulated by the moving window technique. According to Rayner and Fisher the central part of the perceptual span, the *decision region*, includes each letter that subjects can analyse in enough detail to decide whether it is or is not a target. They estimated that the diameter of the decision region was about 3–6 characters, depending on the difference between the target and the distracters. Rayner and Fisher (1987) called the remaining more eccentric part of the perceptual span the *preview region*. It contains partial letter information.

The area that can be processed without the help of any contextual or linguistic information is called the *visual span* (O'Regan, 1990; see also O'Regan, Lévy-Schoen, & Jacobs, 1983; Jacobs, 1986). Visual span reflects purely sensory limitations to perception and can be defined as the “size of the region around the eye's fixation point in which letters can be recognised with a given accuracy” (O'Regan et al., 1983). If we compare the previous definition of the decision region to the definitions of visual span (O'Regan et al., 1983; O'Regan,

1990), they seem to refer to virtually the same thing. The size of the horizontal visual span has been estimated with isolated letters or meaningless strings of letters (O'Regan et al., 1983; Jacobs, 1986). O'Regan et al. (1983) found that the size of the visual span was about 5 letters to the left and right of the fixation point when response accuracy was 90%.

1.2. “Visual span in reading” and word identification span

Legge, Ahn, Klitz, and Luebker (1997) estimated that the horizontal diameter of the *visual span in reading* is about 10.6 characters for text of normal size (character size 0.3–1°). However, Legge et al.'s operational definition of visual span differs from the definition of O'Regan (1990). In the experiment of Legge et al. (1997), subjects read aloud isolated words presented with the rapid serial visual presentation (RSVP) method. Reading speed (words/min) was calculated, and the reading time (ms/word) was determined. Legge et al. (1997) defined visual span in reading as “the reciprocal of the slope from regression lines of reading time vs word length in units of letters/ms, multiplied by 250 ms”. In other words, their operational visual span estimate is the average number of letters recognised during the average fixation duration (250 ms) while reading words. Since Legge et al. used real words instead of meaningless letter strings, the span they estimated might actually be closer to the concept of the *word identification span* (see Rayner, 1998).

Rayner (1998, p. 380) defined the word identification span as the “area from which words can be identified on a given fixation”. Therefore, it is the part of the perceptual span where words can be identified. In an experiment by Underwood and McConkie (1985), subjects read passages of text and occasionally, in certain positions with respect to the reader's point of fixation, letters in the text were replaced by erroneous letters. The changes only damaged the semantic content of the text, leaving the word shapes and spaces between words intact. Underwood and McConkie found that erroneous letters that were eight or more character spaces to the right or four or more character spaces to the left of the fixation point did not affect eye movements in reading. Therefore, while reading, word identification occurred within the area of about 7–8 characters to the right and 3–4 characters to the left of the fixation point. The result is in good agreement with the horizontal span estimate by Legge et al. (1997).

1.3. Visual span control hypothesis and strategy-tactics model

In earlier studies, visual span has been regarded as the primary determinant of saccade size in reading (Legge et al., 1997) and in the visual search of horizontal rows of letters (Jacobs, 1986). Since visual span reflects the

sensory acuity limitations of the retina, the size of the visual span varies as a function of viewing conditions.

The *visual span control hypothesis* (O'Regan et al., 1983) postulates that eye movements are controlled directly in relation to the size of the visual span. However, the evidence is somewhat inconsistent: O'Regan et al. (1983) concluded that saccade sizes in reading were not primarily affected by changes in visual span (they manipulated letter spacing and viewing distance). In contrast, Legge et al. (1997) have shown that, in reading, changes in visual span affect reading speed and eye movements.¹ Legge et al. (1997) found that, when the contrast of the text was low, visual span shrank, resulting in a reduction of reading speed (*the shrinking visual span hypothesis*). With decreasing contrast, reading speed became increasingly dependent on word length because, with decreasing span, longer words needed to be fixated more than once. In the results of Legge et al. (1997), longer reading times at low contrast were partitioned about equally between prolonged fixation times and an increased number of fixations.

On the other hand, in horizontal letter search Jacobs (1986) found that about 80% of the variance of mean saccade sizes, and about 45% of the variation in fixation durations could be explained by the changes in visual span. In his results, changes in the similarity between target and distracters affected the size of the visual span and eye movements. When the target item was hard to discriminate (i.e. the visual span was small), saccade amplitudes were short and constant, whereas fixation durations were long and variable. When the target item was easy to discriminate (i.e. the visual span was large), saccade sizes were longer and more variable, but fixation durations were relatively short and constant. On the basis of the results of Jacobs (1986) and Legge et al. (1997) we can expect that the word identification span can play a part in determining eye movements in visual word search.

However, in addition to the visual span control hypothesis, there is another theoretical approach (see e.g. O'Regan, 1990; Vitu, O'Regan, Inhoff, & Topolski, 1995) which concentrates on the eye movement parameters and eye movement strategies in reading. According to this *strategy-tactics model*, eye movements in reading are globally determined by the careful or risky oculomotor scanning strategy that determines which word to fixate next. This eye movement strategy is only globally adapted to the difficulty of the task. After fixating on the word, the number of possible additional fixations and fixation duration within the word are determined by local tactics, which, among other things, is based on the initial landing position in the word. In the study of Vitu

et al. (1995), there were four different conditions: normal reading, scanning of horizontal letter strings consisting of the letter z, visual search with normal text, and z-string search (subjects searched for a letter c among the horizontal word-like strings consisting of the letter z). They found that the eye movement parameters resembled each other in different conditions, and concluded that since the regular autonomous scanning routine could be acquired in the absence of any linguistic information to process, similar oculomotor strategies might be an important determinant in normal eye movements of reading as well (for criticism, see Rayner & Fischer, 1996).

1.4. Two-dimensional span

Pollatsek, Raney, LaGasse, and Rayner (1993) found that in reading and in horizontal visual word search, subjects obtained little information from below the fixated line. However, in the visual search task, they were occasionally able to obtain information from below the fixated line, but there was no clear evidence that the information available below the fixated line made the search more efficient. The lines above fixation were not investigated. However, Prinz (1984) reported that, in the visual search of letters arranged in horizontal lines, subjects were able to find the target about 3.1 lines (1.8°) below or 2.3 lines (1.3°) above the fixated line. In Prinz's experiment the subjects were instructed to monitor other lines in addition to the currently fixated line. His result gives reason to expect that the word identification span, i.e. the area within which word identification occurs, can be two-dimensional in visual search.

Further, in the human retina, the decline of ganglion cell density with eccentricity is faster in the vertical than in the horizontal direction (Curcio & Allen, 1990). For example, near the fovea (eccentricity of ≈ 0.5 mm) the ratio of the horizontal and vertical diameter of the contour of equal ganglion cell density was 1.28. In more peripheral retina, equal density contours were even more horizontally elongated. The density of ganglion cells is important in visual perception, because it sets the upper limit to the proportion of the spatial information that is transmitted to the brain (Curcio & Allen, 1990). Ganglion cell density, therefore, ultimately determines the area which can be processed by a single fixation. However, other factors such as the crowding effect and attentional limitations probably play a part, too.

1.5. Purpose of the study

The purpose of the first experiment was to estimate the size of the word identification span in the vertical direction. We estimated the vertical word identification span by manipulating the length of vertical word lists

¹ As noted earlier, their operational definition of the visual span in reading might, actually, be closer to the concept of word identification span.

and by monitoring the number of fixations used to identify the target word. The purpose of the second and third experiments was to determine how layout manipulations affect eye movement parameters and the speed of search and how they are related to the word identification span. The vertical word identification span was estimated in experiment 1 and it was compared to the horizontal word identification span estimated in previous studies. In the second experiment we investigated the effect of the line spacing of vertical word lists on threshold search time and eye movements (number of fixations, fixation durations and saccade amplitudes). In the third experiment we manipulated the orientation (horizontal/vertical) and length of the word lists, and measured threshold search time and eye movements.

2. Methods

2.1. Subjects

There were three voluntary female subjects. Subject HO was one of the authors of this paper. The other two subjects were naive as regards the goals of the study. All subjects had normal or corrected to normal vision. All subjects were native speakers of the Finnish language.

2.2. Apparatus and stimuli

The stimuli were generated by using a PC computer with a 200 MHz Pentium MMX Processor and a 17" CRT colour display. The computer was running under the Windows 95 operating system. The graphics adapter was used at a resolution of 800×600 pixels and a frame rate of 85 Hz. The pixel size of the display was 0.0375 cm^2 . The letters on the screen were dark ($\sim 0.3\text{--}1 \text{ cd/m}^2$) on a white background. The photopic luminance of the background was $\approx 100 \text{ cd/m}^2$. A chin rest was used to stabilise the viewing distance and observer's head.

The stimuli were common Finnish verbs, nouns and adjectives, which were presented either in vertical (see Figs. 1 and 7) or horizontal lists (see Fig. 8). The word length was 5–8 letters and the typeface used was upper case Courier New at point size 9. The typeface was non-proportional, i.e. of fixed width. Letter height was about 0.4° (vertical character space 0.6°) at a viewing distance of 57 cm. Letter width was maximally 0.24° (horizontal character space 0.36°).

For each stimulus presentation the distracter words were selected at random from a set of 2640 words. There were seven possible target words: AUKAISTA (= to open, frequency 27 words per million), KUTISTUA (= to shrink, 20), OTTELU (= game/match, 169),

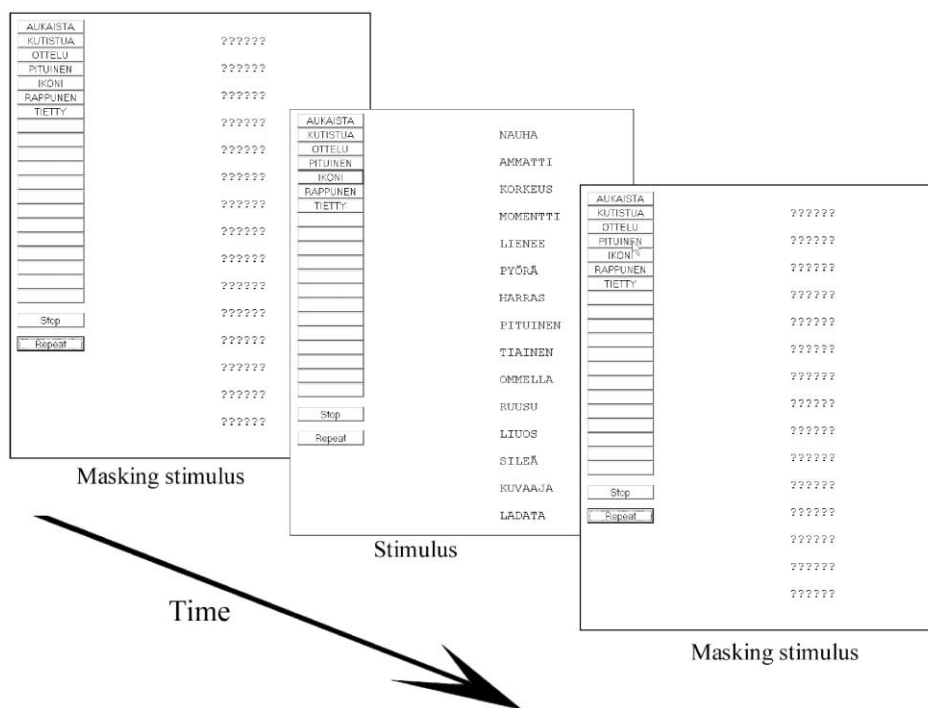


Fig. 1. Accommodation stimuli and a vertical word list of 15 words in experiment 3. The subject was free to fixate anywhere on the masking list before the word list appeared (view on the left). After stimulus presentation (view in the middle) the mask was shown again (view on the right). After the mask had appeared again, the subject gave her response by selecting with the mouse the graphical button corresponding to the target word (view on the right). The subject moved her eyes to the buttons, placed the mouse cursor on the appropriate button, moved her eyes back to the masking stimulus, and pressed the button. A new stimulus appeared 500 ms after pressing the button. A staircase algorithm was used to determine the threshold search time, that is, the presentation time needed for finding the target.

PITUINEN (=length, 96), IKONI (=icon, 17), RAPPUNEN (=step/stair, 17), and TIETTY (=certain, 306). The mean length of the target words was 7 (distracters 6.5) letters and the median length 8 (distracters 6) letters. The words were selected from the frequency dictionary of the Finnish language (Saukkonen, Haipus, Niemikorpi, & Sulkala, 1979). The frequency of the distracter words among Finnish words ranged from 15–482 words per million the median frequency being 42 (the most common Finnish words were left out, as most of them were pronouns or conjunctions). Every list consisted of distracter words selected at random. One of the seven target words was presented in a randomly selected list position. The stimulus presentation was preceded and followed by a similar list constructed by using question marks (?), which served as an accommodation stimulus as well as prevented visual persistence (see Fig. 1). The masking list did not contain information about the word length, since all strings were six characters long.

2.3. Procedure

After clicking the “Start” button or a response button there was a delay of 500 ms before a stimulus list was presented. Prior to the presentation of the stimuli, the mask list was presented (see Fig. 1). Observers were allowed to fixate anywhere on the mask list to encourage the use of their natural search strategies. The task of the subject was to search for and identify a target word from among distracter words on a list. In each list, there was one target word among distracter words. The target in each list could be any of the seven pre-learned target words (aukaista, kutistua ...) with equal probability. The subjects knew that they had to search for one of the seven targets. The purpose of this was to make sure that the target word could not be identified on the basis of a cue like initial letter or word-shape.

Close to the left-hand edge of the screen there was an array of graphical buttons, one button for each of the seven target words. After stimulus presentation (i.e. after the mask list was shown again), the observer indicated her choice by clicking the corresponding button with mouse. The observer first moved fixation to the button array, placed the mouse cursor on the appropriate button, moved fixation back to the masking list and then pressed the mouse button. An auditory feedback signal was given when the observer's choice was incorrect. After the response, a new stimulus list appeared after a delay of 500 ms. The subject was fixating on the masking stimulus, when a new stimulus was presented. The observer was advised to guess if she did not find the target word.

The stimulus presentation time was controlled by a staircase algorithm (Wetherill & Levitt, 1965). At first, the word list was visible for 4000 ms. After three con-

secutive correct responses the stimulus presentation time was reduced by a factor of 1.26, and after each incorrect response, presentation time was correspondingly increased. An estimate for threshold search time at the probability level of 0.79 of correct answers was calculated as the mean of eight reversals. The counting of reversals started after two incorrect responses. The mean number of word lists needed for a single threshold was 50, with a standard deviation of about 10.5 for all three observers and experiments.

2.4. Experiments

In the first experiment we manipulated the length of the vertically arranged word list and measured eye movements and threshold search time in order to determine how many vertically arranged words could be identified during a single fixation. The stimuli consisted of vertical word lists with no blank spaces between the words. The list lengths used were 3–8 items. Each threshold was measured six times, three thresholds of each list length per day. Each list length was measured separately, and different lengths followed each other in succession during each measurement day.

In the second experiment we manipulated the line spacing (interline distance) of the vertical word lists, and measured threshold search time and eye movements. The stimuli were vertical eight-word lists. The list items had either 0, 1, 2, 3, or 4 empty lines (0.6° each) between them. Each measurement was repeated six times, three thresholds of each line spacing per day. Each line spacing was measured separately, and different line spacings followed each other in succession during each measurement day.

In the third experiment we manipulated the orientation (vertical/horizontal) and length (5, 10, 15, and 20 words) of the word lists. In vertical lists, every item was separated by one blank line. Longer horizontal lists had to be cut into five-word lines. Seven blank lines separated the horizontal lines to prevent the subjects from searching multiple lines simultaneously. The threshold search time and eye movements were measured in order to investigate the effect of list layout on search performance and eye movements. Each threshold estimate and eye movement measurement was repeated four times, two thresholds of each list orientation and length per day. Each list length and orientation was measured separately, and different lengths followed each other in succession during each measurement day.²

² Each experiment was measured separately so that the measurements of experiment 3 were done first, experiment 2 next and experiment 1 last. The experiments are presented here in a more logical order from the reader's point of view.

2.5. Eye movement recordings

Eye movements were recorded simultaneously with threshold measurements by using an SMI (Sensomotoric Instruments Inc.) EyeLink video eye tracker. The subjects' gaze position was recorded with miniature infra-red video cameras, while two infra-red LEDs in each camera illuminated the eyes. The cameras were attached to a headband worn by the subjects. The sampling rate of the system was 250 Hz. The eye tracking system was controlled by a separate PC computer running under the DOS operating system. The eye tracker computer was interfaced with the previously mentioned stimulus presentation computer via an Ethernet link. A chin rest was used to stabilise the observer's head.

The registration of eye movements started simultaneously with stimulus presentation and was automatically switched off when the subject made an eye movement to the response buttons, when stimulus presentation ended, or when the mouse button was pressed. The observers were instructed to make an immediate saccade to the response buttons after finding the target word. The purpose of these measures was to ensure that the collected data reflect real search performance and not eye movements made after the target was found. The collection of eye movement data started after the subject had made two errors in her responses. The eye movement data, thus, represent the behaviour at near threshold level.

The saccades and fixations were detected automatically using software provided by the manufacturer of the eye tracker. A sample was regarded as belonging to a saccade if either the acceleration or velocity exceeded their respective thresholds ($9500^\circ \text{ s}^{-2}$ for acceleration or 35° s^{-1} for velocity) for that sample. Other samples belonged to a fixation. The means of the eye position data for the left and right eye were calculated and used in further analyses.

2.6. Statistical procedure

Eye movement and performance data were analysed by using a repeated measures ANOVA. Because of the relatively small sample size, the degrees of freedom were corrected with the Huyhn–Feldt correction to meet the sphericity assumption of the covariance matrix. Non-integer degrees of freedom are, therefore, reported.

3. Results

3.1. Experiment 1: vertical word identification span

In experiment 1 we estimated the vertical word identification span by increasing the length of the vertical word list, and by measuring the number of fixations

needed to recognise the target word on the list. Fig. 2 shows the effect of list length on threshold search time and on the number of fixations per search. The estimate for the vertical diameter of the span was the height of the longest word list that could be processed during a single fixation.

Threshold search time ($F(4.58, 9.15) = 68.23$, $p < 0.001$) and mean number of fixations ($F(5, 10) = 49.99$, $p < 0.001$) increased with increasing list length. The increase in threshold search time was linear ($F(1, 2) = 107.74$, $p < 0.01$). Only one fixation was needed for the list of three words. For the list of four words, subjects HO, MK and EI had an average of 1, 1.1, and 1.009 fixations per search, respectively. With longer lists there was clearly more than one fixation. The limit of the vertical word identification span was estimated as the intersection of a regression line fitted to the data for list lengths of 5–8 words, which clearly deviate from unity, and a horizontal line representing a single fixation (see Fig. 2, right column). For subjects HO, MK and EI the estimates of vertical word identification span were 4.3, 3.9 and 4.9 character spaces, respectively. The mean fixation duration for the longer lists was about 220 ms, and the mean saccade amplitude was about 1.2 character spaces (1.40°).

3.2. Experiment 2: effect of line spacing

In experiment 2 we manipulated line spacing (inter-line distance) of vertical word lists, and measured eye movements and threshold search time. The stimuli were vertical eight-word lists. The list items had either 0, 1, 2, 3, or 4 empty lines (0.6° each) between them. The data in Fig. 3 shows the effect of line spacing on threshold search time and on the number of fixations. Fig. 4 shows the effect of line spacing on fixation duration and on saccade amplitude. The data presented in Figs. 3 and 4 represent the arithmetic means of the six measurements made on different days.

With increasing line spacing, the threshold search time ($F(4, 8) = 5.85$, $p < 0.05$), mean number of fixations per search ($F(2.06, 4.12) = 15.07$, $p < 0.05$) and mean saccade amplitude ($F(3.09, 6.18) = 46.4$, $p < 0.001$) increased, the saccade amplitude linearly ($F(1, 2) = 70.64$, $p < 0.05$). Mean fixation duration did not change statistically significantly with increasing line spacing ($F(1.25, 2.49) = 10.69$, $p = 0.061$ ns). The results indicate that the subjects used more saccades and fixations to examine the list when the same number of items was spread over a wider area. The increase in search time with increasing line spacing can be explained by increase in the number of fixations since in all experiments, the number of fixations per search and threshold search time were highly correlated (see Table 1).

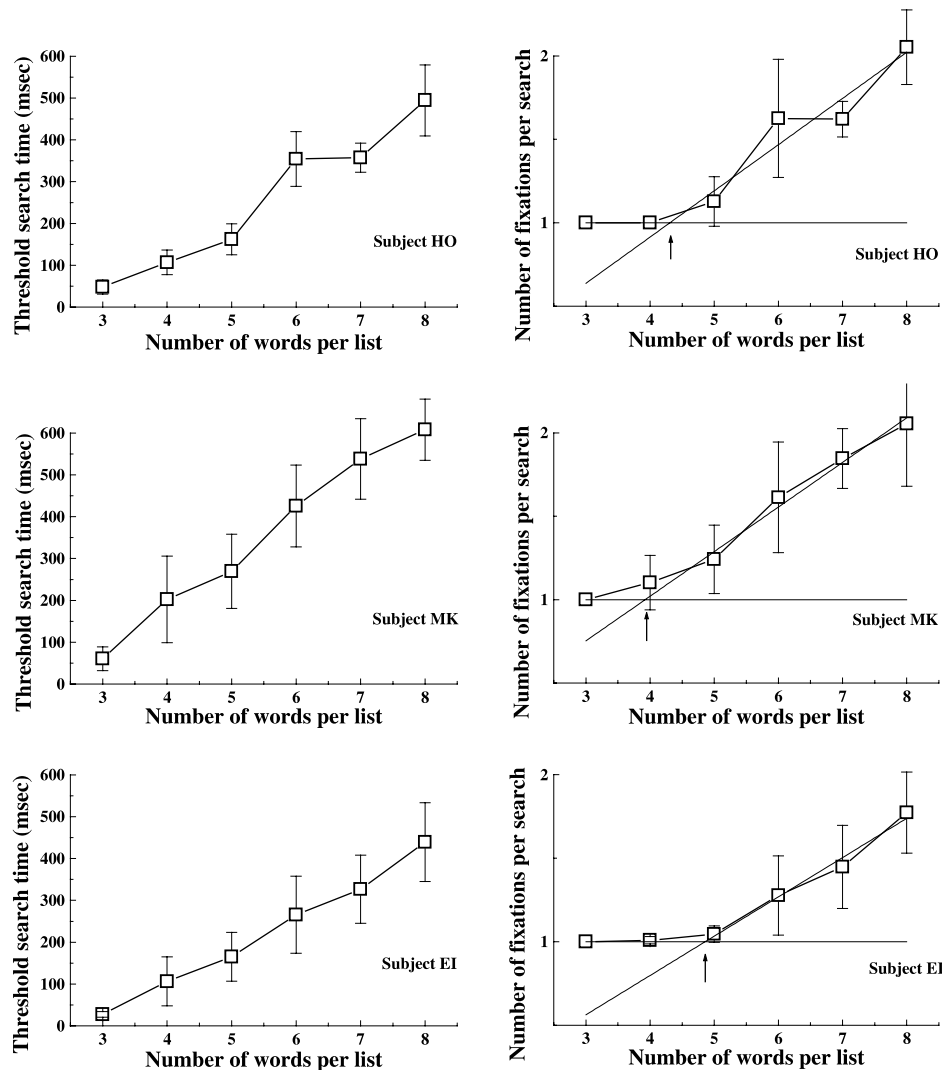


Fig. 2. Threshold search time (left column) and the number of fixations per search (right column) as a function of vertical list length. Error bars show the 95% confidence interval for the means (mean $\pm 2.45 \times \text{SEM}$). The limit of the vertical word identification span was estimated as the intersection of a regression line fitted to the data for list lengths 5–8, which clearly deviate from unity, and a horizontal line representing a single fixation. Intersections are indicated with vertical arrows. Equations for regression lines: for subject HO $y = 0.2771x - 0.19416$ ($R = 0.946$), for subject MK $y = 0.26741x - 0.049$ ($R = 0.990$), and for subject EI $y = 0.23527x - 0.14297$ ($R = 0.992$). The vertical visual span estimates for subjects HO, MK and EI were about 4.3, 3.9 and 4.9 character spaces, respectively.

3.3. Experiment 3: visual search in vertical and horizontal lists

In experiment 3 we manipulated list orientation and list length. Threshold search time for identifying a target word was measured, and eye movements were recorded simultaneously.

The data in Fig. 5 shows the effect of list length and list orientation on threshold search time and on the number of fixations per search. There was no statistically significant difference in search times as a function of list orientation ($F(1, 2) = 6.49$, $p = 0.126$ ns). For vertical lists, however, there were less fixations per search than for horizontal lists ($F(1, 2) = 50.42$, $p < 0.05$). With increasing list length, threshold

search time ($F(2.05, 4.10) = 91.91$, $p < 0.001$) and the number of fixations ($F(1.09, 2.17) = 267.72$, $p < 0.01$) increased linearly.³

Fig. 6 shows the effect of list length and list orientation on mean fixation duration and on saccade amplitude. Mean fixation durations were longer ($F(1, 2) = 46.93$, $p < 0.05$) for vertical lists than for horizontal lists. Saccade amplitudes were greater for horizontal lists ($F(1, 2) = 49.75$, $p < 0.05$). Mean fixation duration ($F(3, 6) = 24.05$, $p < 0.01$) and saccade amplitude ($F(3, 6) = 5.01$, $p < 0.05$) increased slightly with increasing list length. There was no statistically significant

³ Linearity of search time ($F(1, 2) = 554.01$, $p < 0.01$) and number of fixations ($F(1, 2) = 3725.50$, $p < 0.001$).

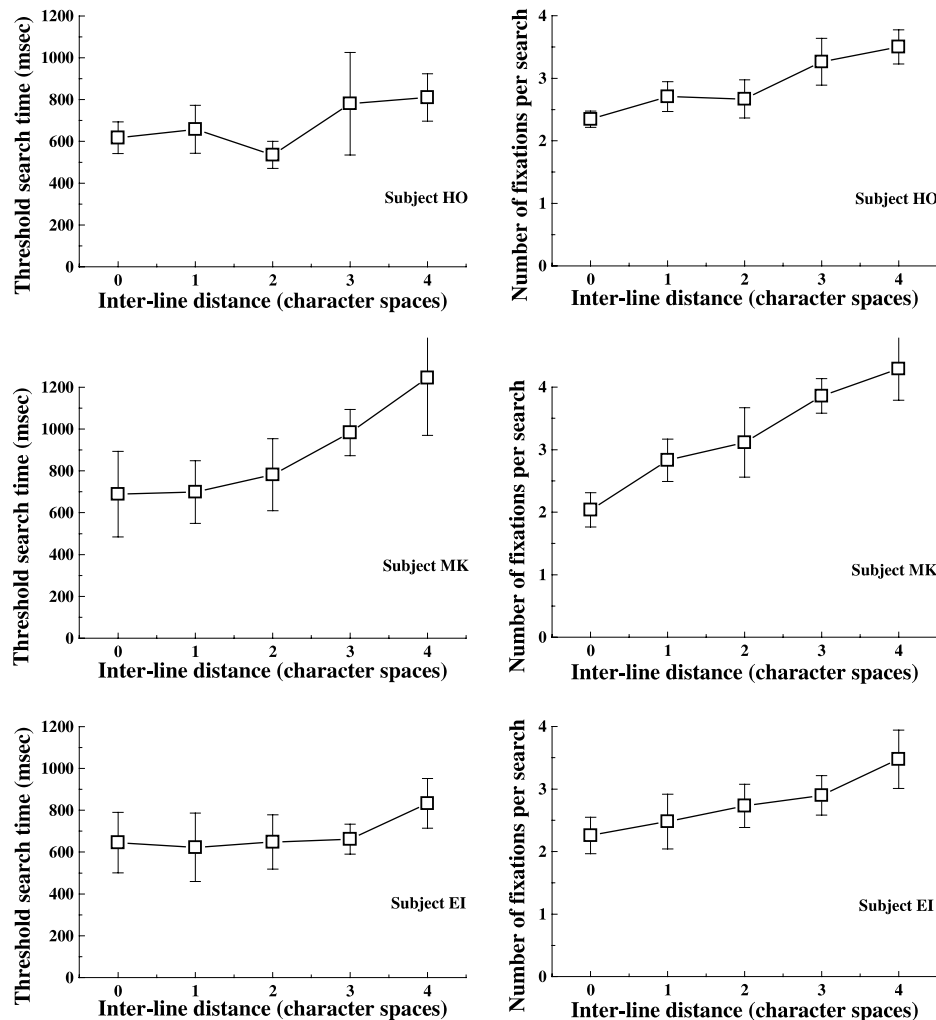


Fig. 3. The effect of line spacing (inter-line distance) on threshold search time (left column) and the number of fixations per search (right column). The stimuli were vertical eight-word lists. List items had either 0, 1, 2, 3, or 4 empty lines (0.6° each) between them. Both threshold search time and the number of fixations increased statistically significantly with increasing inter-line distance. Error bars show the 95% confidence interval for the means (mean $\pm 2.45 \times \text{SEM}$).

interaction between list length and list type.⁴ The data reveal that eye movement patterns depend on list orientation although the threshold search time does not.

In experiment 3, the average threshold search time was 450 ms for lists of five words, whereas it was 198 ms for the same list length in experiment 1. It would seem that this difference does not result from a difference in line spacings, since according to experiment 2 there is no difference in threshold search times between line spacings of 0 and 1. We attribute this difference to a learning effect across experiments, since experiment 3 was measured first, experiment 2 next, and experiment 1 last. We did a control experiment with vertical lists of five words,

where we manipulated the line spacing (0 or 1). The line spacing did not have an effect on search times. In the control experiment, the search time was 277 ms on average, which is less than in experiment 3 but more than in experiment 1. This supports the interpretation that the differences between experiments 3 and 1 probably result from a learning effect (and some forgetting between experiment 1 and the control experiment measured several months later). The learning effect did not affect the findings within each experiment, since the different conditions were performed in a counter-balanced order.

4. Discussion

The estimate for the word identification span in a vertical direction was 4–5 character spaces ($2.4\text{--}3.0^\circ$), i.e.

⁴ Threshold search time $F(1.55, 3.10) = 2.20$, $p = 0.248$ ns. Number of fixations: $F(3, 6) = 3.86$, $p = 0.075$ ns. Fixation duration: $F(1.33, 2.66) = 3.47$, $p = 0.176$ ns. Saccade amplitude $F(1.63, 3.26) = 0.12$, $p = 0.858$ ns.

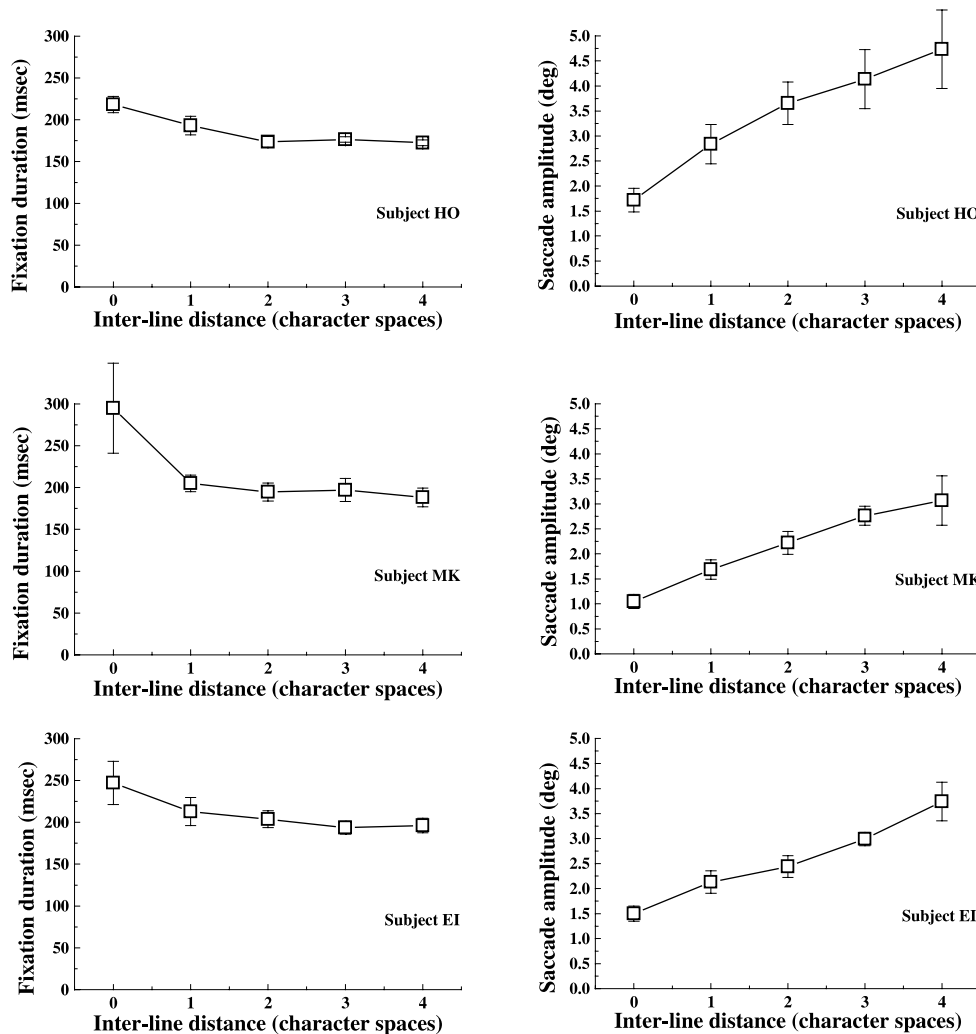


Fig. 4. The effect of line spacing (inter-line distance) on mean fixation duration (left column) and saccade amplitude (right column). The stimuli were vertical eight-word lists. List items had either 0, 1, 2, 3, or 4 empty lines (0.6° each) between them. Saccade amplitude increased linearly with increasing inter-line distance. Mean fixation duration did not change statistically significantly with increasing inter-line distance. The post hoc pairwise comparison revealed no statistically significant difference between fixation durations between line spacings 0 and 1, either ($p = 0.133$). Error bars show the 95% confidence interval for the means ($\text{mean} \pm 2.45 \times \text{SEM}$).

Table 1
Pearson's correlations between the number of fixations and threshold search time in experiments 1–3

Experiment	All subjects	Within subjects		
		HO	MK	EI
1	0.939**	0.965**	0.946**	0.931**
2	0.818**	0.793**	0.819**	0.810**
3	0.943**	0.965**	0.946**	0.947**

** $p < 0.01$, the difference of the correlation coefficient from zero, two-tailed.

the subjects were able to identify on average 4.4 vertically arranged words during a single fixation. On average, 4.4 words contained altogether 28.6 letters. There were less fixations for vertical lists than for horizontal lists of similar length. The mean fixation durations were

longer and saccade amplitudes were smaller for vertical than for horizontal lists. With increasing list length or line spacing, threshold search time increased in parallel with the increase in the number of fixations per search. In general, the number of fixations per search correlated highly with threshold search time in all experiments.

4.1. Comparison of vertical and horizontal span estimates

We compared our vertical estimate to the horizontal visual span and horizontal word identification span estimates, which most closely correspond to our estimate. When expressed in characters, the vertical word identification span seems to be smaller than the horizontal visual span estimate by Legge et al. (1997), which was 10.6 characters. It is also smaller than the horizontal

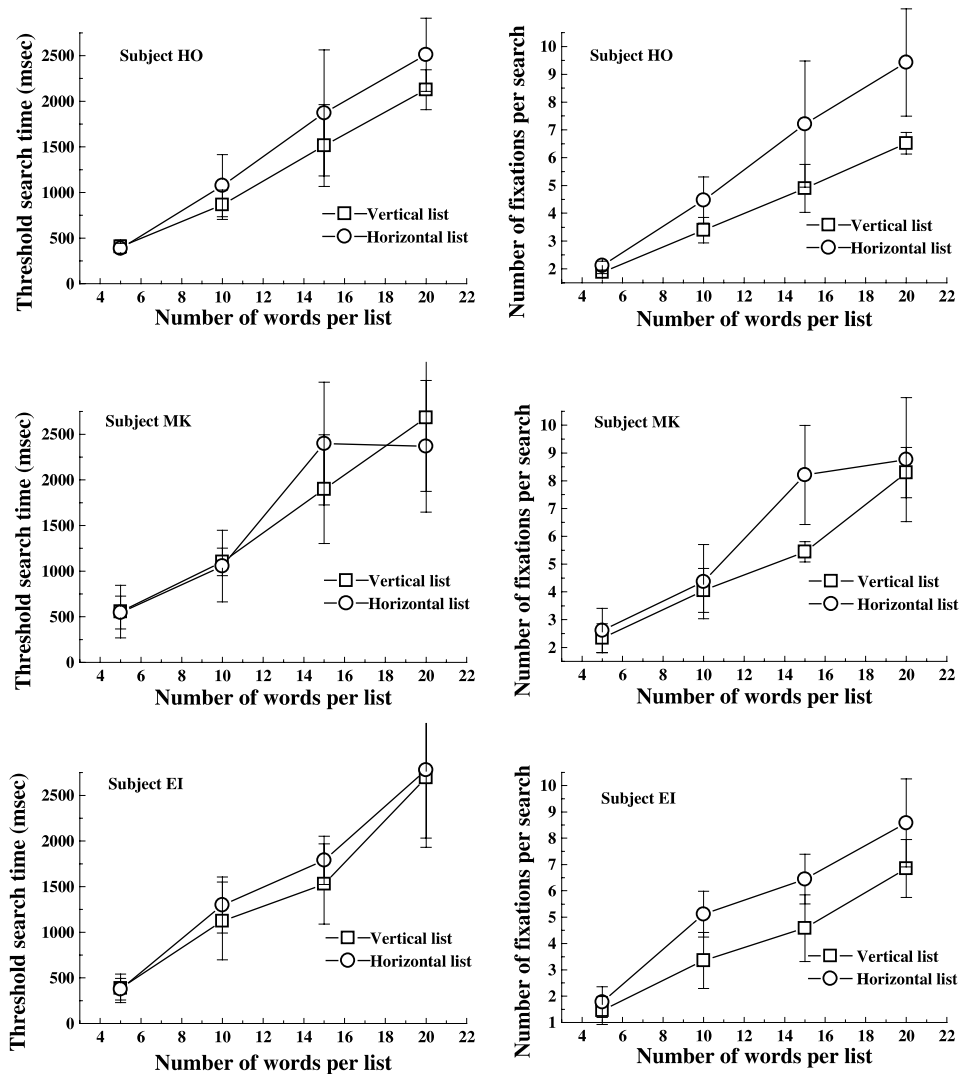


Fig. 5. The effect of list orientation and list length on threshold search time (left column) and the number of fixations per search (right column). The stimuli were either horizontal or vertical word lists, and the list lengths used were 5, 10, 15, and 20 words. Threshold search time as well as the number of fixations per search increased linearly with increasing list length. For vertical lists, there were statistically significantly less fixations than for horizontal lists. List orientation did not have a statistically significant effect on threshold search time. Error bars show the 95% confidence interval for the means (mean $\pm 2.77 \times \text{SEM}$).

word identification span in reading (Underwood & McConkie, 1985; Rayner, 1998), which was about 7–8 character spaces to the right of fixation and 3–4 character spaces to the left of fixation.

For comparing the vertical and horizontal estimates of span, they must be converted to comparable units. The characters used in our experiments were larger in vertical than in horizontal direction (1.65:1). We converted Legge's horizontal estimate (originally in character widths) to character heights: 10.6 character widths corresponds to 6.42 character heights. We calculated the ratio of the horizontal to vertical span estimates by dividing the converted horizontal estimate of Legge by our mean vertical estimate (6.42/4.37) and obtained a value of 1.47. We calculated the ratio between horizontal and

vertical word identification span similarly⁵ and obtained a value of 1.53. Therefore, the two-dimensional area from which words can be identified seems to be elongated in the horizontal direction.

The horizontally elongated two-dimensional span appears to be in agreement with Wertheim's (1894) classical visual acuity results. He reported that visual acuity declines with eccentricity so that the contours of equal visual acuity are roughly elliptical. Similarly, the sizes of the vertical and horizontal span estimates are roughly in agreement with the anatomical results of

⁵ Horizontal word identification span (7.5 + 3.5 letters = 11 letters, which corresponds 6.67 letter heights) vs. vertical word identification span: 6.67/4.37.

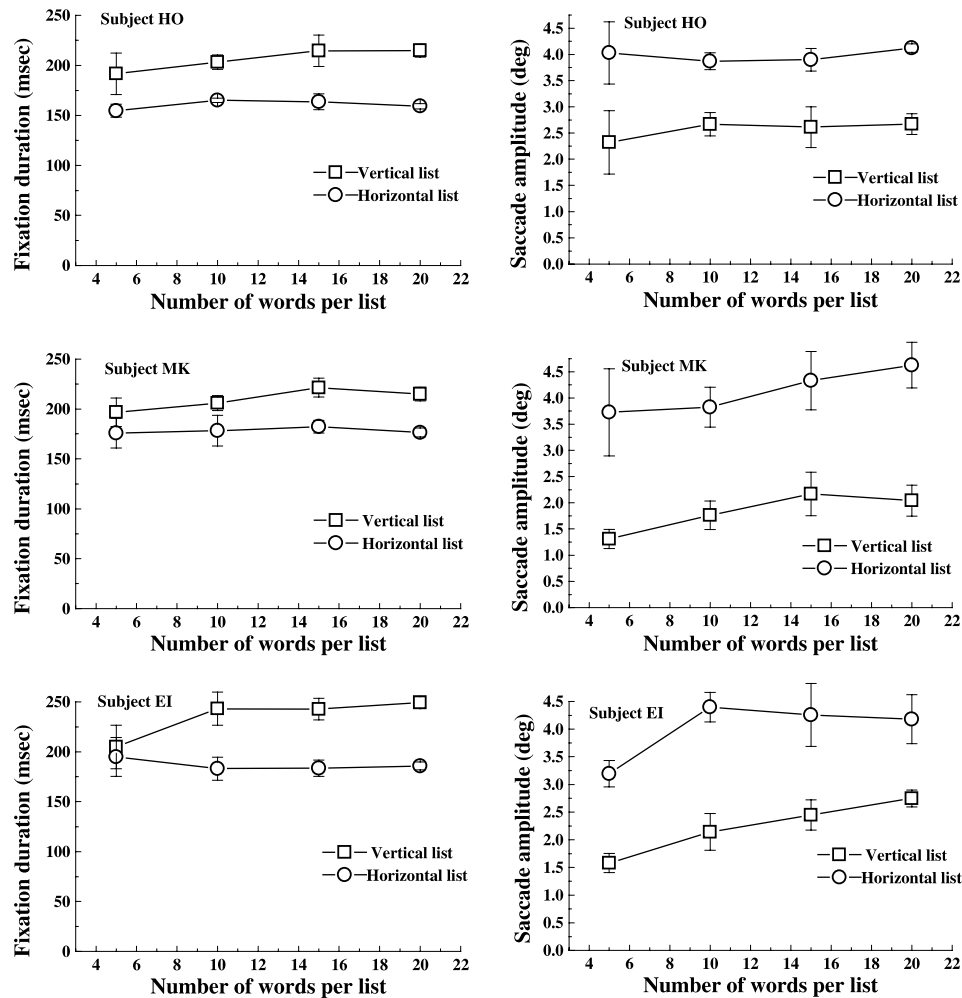


Fig. 6. The effect of list orientation and list length on mean fixation duration (left column) and saccade amplitude (right column). The mean fixation duration was longer and saccade amplitude was smaller for vertical lists. With increasing list length, the mean fixation duration and saccade amplitude increased statistically significantly. Error bars show the 95% confidence interval for the means (mean $\pm 2.77 \times \text{SEM}$).

Curcio and Allen (1990). They reported that the retinal ganglion cell density in humans declines with eccentricity so that the diameters of the equal density contours are horizontally longer than vertically. For example, in the central retina, the ratio of the horizontal diameter of the equal ganglion cell density contour to its vertical diameter was 1.28. In the peripheral retina, the ratio was 1.59 (i.e. the contour of equal ganglion cell density was horizontally more elongated than near the fovea). The two ratios calculated for vertical and horizontal span estimates lie between the two ratios reported by Curcio and Allen (1990). This suggests that the sizes of the span estimates reflect, at least partially, sensory limitations of visual perception. Attentional limitations and lateral masking may also play a role in the word identification process, however.

Taken together, the results discussed so far suggest that when the stimulus material is presented two-dimensionally (like in vertical lists in experiment 1), the word-identification span is two-dimensional. Further,

the shape of the two-dimensional span seems to be roughly elliptical (height being about 4–5 character spaces and width about 10 character spaces).

4.2. Two-dimensional span and stimulus layout

The difference in vertical and horizontal diameters of the two-dimensional word identification span explain most of the effects of list orientation on eye movements found in experiment 3. In the first experiment about 4.4 words could be processed during a single fixation in vertical lists. This corresponds to 28.6 letters, whereas horizontal arrangement of words allows only 10–11 letters (1–2 words) to be processed during single fixation. This means that although the vertical diameter of the span is smaller than the horizontal diameter (in terms of characters), the vertical arrangement allows much more information to be processed during a single fixation. In other words, vertical lists fit the area of word identification span more effectively than horizontal lists.

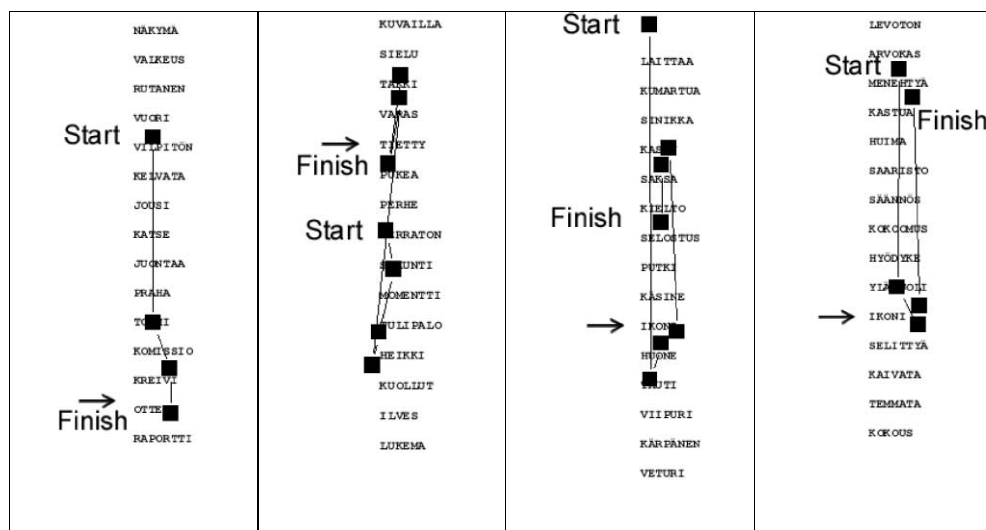


Fig. 7. Samples of typical vertical scan paths for subjects EI (figure on the right) and MK (the others). The subjects searched vertical lists of 15 words. Fixations are indicated with black squares. The scan path begins at “Start” and ends at “Finish”. The target word is indicated with an arrow. Sometimes a few fixations are made after the subject has fixated on the target (two figures on the right) and sometimes the search terminates when the target is fixated on (two figures on the left). The scan path may be linear (figure on the left), v-shaped (figure on the right) or more complex (two figures in the middle). Saccade amplitude varies considerably.



Fig. 8. Samples of typical horizontal scan paths for subjects EI (top figure on the left) and MK (the others). The subjects searched horizontal lists of 15 words. Fixations are indicated with black squares. The scan path begins at “Start” and ends at “Finish”. The target word is indicated with an arrow. Sometimes the paths resemble reading (figures on the right) and sometimes not (figures on the left). As in vertical lists, saccade amplitude varies.

It follows that more fixations are needed for horizontal lists than for vertical lists of similar length. Also longer saccade amplitudes are used in horizontal than in vertical direction, because the two-dimensional word

identification span is wider in the horizontal direction. The result has relevance for example in the design of user interfaces (computers, web-pages etc.). According to our data, information (e.g. menus) should be ar-

ranged vertically rather than horizontally to make the use of eye movements more economical in visual search.

The word identification span also explains the effects of list length (experiments 1 and 3) and line spacing (experiment 2). When list length increases, more fixations are needed, because longer lists do not fit the word identification span. With increasing line spacing, the same amount of information is distributed over a larger area, and again, more fixations are needed. The increase in the number of fixations explains the increased threshold search time with increasing list length and line spacing, since fixations take most of the time in search. This is reflected as high correlation between threshold search time and the number of fixations (see Table 1). The high correlation is in good agreement with earlier studies, in which the speed of visual search and eye movements have been investigated in the context of traditional visual search stimuli (see e.g. Williams, Reingold, Moscovitch, & Behrmann, 1997).

The threshold search times for vertical and horizontal lists did not differ statistically significantly. This is due to the longer mean fixation duration for vertical lists, which compensates for the effect of the increased number of fixations in horizontal lists. The mean fixation duration in our results was on average 41 ms longer in vertical than in horizontal lists. This is qualitatively, although not quantitatively, in agreement with the results of O'Regan et al. (1983). They found that when the number of letters within one fixation increased by two letters, the fixation durations increased about 10 ms. Our results support the view that the increase in the number of items processed during a single fixation increases fixation duration.

There was a linear increase in saccade amplitude with increasing line spacing in experiment 2. This increase may partially result from inter-line distance exceeding the size of the word identification span.⁶ This does not, however, explain the increase of saccade amplitudes in small line spacings (see Fig. 4, right column). However, the span may have increased with small line spacings because of a reduction in the crowding effect, which could explain the increase in saccade amplitude from spacing 0 to 1.

The saccade amplitudes and fixation durations increased slightly with increasing list length in experiment 3. These changes may result from the threshold measurement procedure, which encourages observers to search with a “risky strategy” especially in longer lists: the observer is aware of the short stimulus presentation time, and tries to view the whole list by using longer

saccades, and, at the same time, is in risk to miss words between fixations. This results in weak visibility of the outermost words during each fixation, which may be reflected as prolonged processing time (i.e. increased fixation durations).

4.3. Current theories and word search strategies

The mean number of fixations, mean fixation duration, and mean saccade amplitude support the visual span control hypothesis quite well. This suggests that sensory factors play a part in determining eye movements in visual word search. However, when we observe the individual search trials (see examples in Figs. 7 and 8), we see that the variability of the saccade amplitude is large, resulting in highly irregular scan paths. Also the sequence of the fixations in scan paths appears to be irregular. Therefore, the relation between the word identification span and scan paths in visual word search seems to be more complex than predicted by the visual span control hypothesis for reading. However, the exact relation between individual scan paths and information processing during word search is beyond the scope of the present study. In a word search task, the word-identification span might be one determinant of a globally adapted strategy (see O'Regan, 1990). However, on the basis of our results it is not possible to conclude as to how much the saccade amplitudes and scanning strategies are globally determined in word search.

5. Conclusions

The results show that the word identification span can be two-dimensional and horizontally elongated. This is in agreement with the decline of visual acuity and ganglion cell density of the human retina as a function of eccentricity. The shape of the two-dimensional word identification span explains the differences found in the speed of visual search and in average eye movement parameters in different list configurations. In addition, average fixation durations are affected by the amount of information (number of items) within the span. However, the relationship between the word identification span and eye movements in individual scan paths in visual search seems to be more complex than proposed by the visual span control hypothesis.

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⁶ The observer does not have to fixate to the totally blank area to see whether there are items. When the line spacing is large, the observer fixates to the next item instead of blank space between words, and saccade amplitude becomes greater than the corresponding span would require.

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